

## **Final Report to the NASA Earth-Science Program**

**Award Number:** NAG5-11773

**Title:** Application of Satellite Altimeter Data to Studies of Ocean Surface Heat Flux and Upper Ocean Thermal Processes (One Year Extension of NAG5-7949)

**Duration:** 3/1/02-2/28/03

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### **1. Major Results**

This is a one-year cost extension of previous grant (NAG5-7949) but carrying a new award number (NAG5-11773) for the administrative purpose. Supported by this one-year extension, the following research has continued and obtained significant results. 20 papers have been published (9) or submitted (11) to scientific journals in this one-year period (NASA support was acknowledged in these papers, see the publication list in section 2). A brief summary of scientific results on: 1. A new method for estimation of the sensible heat flux using satellite vector winds, 2. Pacific warm pool excitation, earth rotation and El Niño Southern Oscillations, 3. A new study of the Mediterranean outflow and Meddies at 400-meter isopycnal surface using multi-sensor data, 4. Response of the coastal ocean to extremely high wind, and 5. Role of wind on the estimation of heat flux using satellite data, are provided below as examples of our many research results conducted in the last year.

### **1.1 A New Method for Estimation of the Sensible Heat Flux using Satellite Vector Winds**

It has been difficult to estimate the sensible heat flux in the air-sea interface using satellite data because of the difficulty in remotely observing the sea level air temperature. In this study, we first developed a new method for estimating the sensible heat flux using satellite observations under unstable conditions. The basic idea of the method is that the air-sea temperature difference is related to the atmospheric convergence. The employed data include the wind convergence, sea level humidity and sea surface temperature. These parameters can be derived from the satellite wind vectors, Special Sensor Microwave/Imager (SSM/I) precipitable water, and Advanced Very High Resolution Radiometer (AVHRR) observations, respectively. We selected a region east of Japan as the test area where atmospheric convergence appears all year around. Comparison between the heat fluxes derived from the satellite data and from the National Centers for Environmental Prediction (NCEP) data suggests that rms difference between the two kinds of sensible heat fluxes has low values in the sea area east of Japan with a minimum of  $7.5 \text{ W/m}^2$ . A good agreement is found between the two kinds of sensible heat fluxes at 12 locations in the area with rms difference range between  $9.7 \text{ W/m}^2$  and  $12 \text{ W/m}^2$ . Further comparison shows that after removing the annual cycles from the sensible heat fluxes, the interannual variations are still in good agreement. (*J. Phys. Oceanogr., Submitted*)

### **1.2 Pacific Warm Pool Excitation, Earth Rotation and El Niño Southern Oscillations**

The interannual changes in the Earth's rotation rate, and hence in the length of day (LOD), are thought to be caused by the variation of the atmospheric angular momentum (AAM). However, there is still a considerable portion of the LOD variations that remain unexplained. Through analyzing the non-atmospheric LOD excitation contributed by the Western Pacific Warm Pool (WPWP) during the period of 1970-2000, the positive effects of the WPWP on the interannual LOD variation are found, although the scale of the warm pool is much smaller than that of the solid Earth. These effects are specifically intensified by the El Niño events, since more components of the LOD-AAM (AAM removed) were

accounted for by the warm pool excitation in the strong El Niño years. This research was selected by the AGU editors for an AGU press release, and has attracted significant attention, not only because it is an important geodetic issue but also because it has significant value as a global measure of variations within the hydrosphere, atmosphere, cryosphere and solid Earth, and hence the global changes. (*Geophys. Res. Lett.* 29(21):15685-15690, 2002).

### **1.3 A New Study of the Mediterranean Outflow and Meddies at 400-meter Isopycnal Surface using Multi-Sensor Data**

Previous studies of the Mediterranean Outflow and Meddies (O&M) were limited by the poor spatial and temporal resolution of conventional observations. Little is known about the formation and transport of Meddies, and the spatial and temporal variation of their trajectories. Generally speaking, most satellite observations are confined to the ocean's surface or its surface layer, however Meddies are typically located, on an average, at a depth of 1000m. We developed a new remote sensing method to observe and study the O&M through unique approaches in satellite multi-sensor data integration analyses. Satellite altimeter, scatterometer, SST and XBT data were used to detect and calculate the trajectories and the relative transport of the O&M. Two experiments, *A Mediterranean Undercurrent Seeding Experiment* (AMUSE) and *Structures des Echanges Mer-Atmosphere, Proprietes des Heterogeneites Oceaniques: Recherche Experimentale* (SEMAPHORE), from 1993 to 1995 were used to directly validate our method. Additionally, the vertical temperature profile that reaches the 700m depth, as determined by XBTs, was used to indirectly validate our method, since vertical temperature structure differs in the presence of a Meddy. The monthly mean features derived from floats and XBTs for Meddies and the results of our method were significantly correlated based on a statistical chi-square test. In the analysis, we found that more Meddies moved northwestward in the spring and southward in the fall. Stream functions, using TOPEX/Poseidon (T/P) altimetry, and time-frequency energy distributions, using the Hilbert-Huang Transform (HHT), were computed to evaluate the Meddy interactions with the sea surface variation. Since the O&M play a significant role in carrying salty water

from the Mediterranean into the Atlantic, such new knowledge about their trajectories, transport, and life histories is important to the understanding of their mixing and interaction with North Atlantic water. This may lead to a better understanding of the global ocean circulation and global climate change. (*J. Geophys. Res., Submitted*)

#### **1.4 Role of Wind on the Estimation of Heat Flux using Satellite Data**

The heat storage anomaly of the upper ocean can be estimated using altimeter data, based on the thermal expansion equation. However, the errors in such calculation have not been fully evaluated. In this study, we analyzed errors in the calculation of the heat storage anomaly in the global oceans and the influence of wind stress on this error. The TOPEX/Poseidon altimeter  $1^{\circ} \times 1^{\circ}$  sea surface height anomaly from January 1993 to October 2000 were used for the calculation of the heat storage anomaly. In addition, we used expandable bathythermograph (XBT) from the global oceans to determine a reference heat storage, from which the altimeter estimation of the heat storage was compared. The wind stress curls, from scatterometer data, were used for analyzing the wind effects on the errors. The correlation coefficients between the heat storage from altimeter data and that from the XBTs are larger than 0.6 in the global oceans, except in the regions of  $20^{\circ}$  E in the eastern Pacific, the eastern tropical Pacific, the tropical Atlantic and the western tropical Indian Ocean. The root mean square of the error has large values in the Gulf Stream and the Kuroshio Extension regions as well as the eastern and western tropical Pacific, and eastern Indian Ocean. The heat storage estimation error has strong annual and interannual cycles, so the EOF method was employed to extract the cycles. The annual cycle has two modes, whereas the interannual cycle is characterized by El Niño events. Wind stress can affect the estimation of the heat storage through mechanisms derived from quasi-geostrophic and barotropic theory. We calculated the correlation coefficient between the error and wind stress curl. The result shows that El Niño Southern Oscillation (ENSO) related wind stress curl anomalies are responsible for the estimation errors in the regions west of South and North America and tropical oceans. The high correlation suggests that in these regions the barotropic and linear theory is the dynamic mechanism of the wind effects on the heat storage estimation. However,

baroclinic signal in sea level is dominant in the tropical oceans. The effect of wind forcing has the most important role in the sea level change during the 1997-98 El Niño event. For instance, the heat storage anomaly ( $Q'$ ) in the west coast of Peru closely relates to sea surface temperature (SST), wind forcing, remnant sea level height anomaly ( $\Delta\eta'$ ), and Ekman depth ( $D_{EK}$ ) due to the strong coastal upwelling. The  $Q'$  in the west coast of America and western Pacific warm pool areas however, did not closely relate to SST, wind forcing,  $\Delta\eta'$ , and  $D_{EK}$ . (*J. Geophys. Res., Submitted*)

### **1.5 Response of the Coastal Ocean to Extremely High Wind**

This study deals with the ocean response to episodic high winds with emphasis on the behavior of the ocean at the shelf-break. For this reason, the test site is selected at the DeSoto Canyon in the northeast Gulf of Mexico, and the event, the passage of 1998 Hurricane Georges with a maximum wind speed of  $47 \text{ ms}^{-1}$ . The data sets we used consist of the mooring data taken by the Field Program of the DeSoto Canyon Eddy Intrusion Study, and simultaneous winds observed by NOAA (National Oceanic and Atmospheric Administration) Moored Buoy 42040. Time-depth inertial energy images derived from the observation data show that the ocean responds almost immediately to the Hurricane with important differences on and off the shelf. On the shelf, in the shallow water of 100 m, the disturbance penetrates rapidly downward to the bottom and forms two energy peaks, with the major peak located in the mixed layer and the secondary one near the bottom. The response dissipates quickly after external forcing disappeared. Off the shelf, in the deep water, the major disturbance energy seems to be trapped in the mixed layer with a trailing oscillation at the inertial period; although the disturbance signals may still be identified at the depths of 500m and 1290m. We model the behavior of pre-existing inertial oscillations in a two-layer model ocean with a frequency of about 1 cpd subjected to a soliton-like wind field theoretically. The theoretical solution reveals that the forced current field consists of three components: the pre-existing inertial oscillation, and amplitude-modulated, forced oscillations. Theoretical model agrees with the observations very well. (*J. Phys. Oceanogr., Submitted*)

These are examples of our many research results conducted in the last year.

## 2. Publications Supported By This One-Year Extension

1. Jo, Young, **Yan, X.-H.**, and J. Pan, 2002. Calculation of the Bowen Ratio in the tropical Pacific using satellite sea surface data. *J. Geophys. Res.* 107 (C9): 17, 1-16.
2. Zheng, Q., Y. Yuan, V. Klemas, and **X.-H. Yan**. 2002. Theoretical Expression for an Ocean Internal Soliton SAR Image and Determination of the Soliton Characteristic Half Width. *J. Geophys. Res.*, Vol. 106 (C12):31415-31423.
3. Kabbara, N., **X.-H. Yan**, and V. Klemas J. Pan. 2002. Temporal and spatial variability of the surface temperature anomaly in the levantine basin of the Eastern Mediterranean, *International Journal of Remote Sensing*, 23 (18): 3745-3761
4. Zheng, Q. V.Klemas, **X.-H.Yan**, 2002. Advance in studies of ocean internal waves observed from space, in recent research developments in geophysics, *Research Signpost*, 4, 143-156
5. Pan, J. **X.-H. Yan**, Q. Zheng, W. T. Liu, and V. Klemas. 2002. Interpretation of Scatterometer Ocean Surface Wind Vector EOFs in the Northwestern Pacific. *Remote Sensing of Environment*, 84 (2002): 53-68
6. Pan, J. **X.-H. Yan**, Q. Zheng, and W. T. Liu. 2002. Observation of Western Boundary Current Atmospheric Convergence Zones Using Scatterometer Winds. *Geophysical Research Letters*. 29, 1832-1853.
7. **Yan, X.-H.**, J. Pan, Y. Zhou, X. Liao, M. He, M. Fang, 2002, Pacific Warm Pool Excitation, Earth Rotation and El Nino Southern Oscillations. *Geophysical Research Letters*. Vol 29, No. 21, 15685-15690.
8. Liu, Y., and **X.-H. Yan**, 2003, Directional Spectrum of Wind Waves: Part I-Model and Derivation. *J. of Oceanic and Coastal Sea Research*, Vol. 2, No. 1, pp. 1-12
9. Liu, Y., and **X.-H. Yan**, 2003, Directional Spectrum of Wind Waves: Part II-Comparison and Confirmation. *J. of Oceanic and Coastal Sea Research*, Vol. 2, No. 1, pp. 23-23
10. Zhang, X., and **Yan, X.-H.**, 2002, A Numerical Study of the Mean Upper Ocean Circulation in the South China Sea. *J. Phy. Oceanogr.*. Submitted.
11. **Yan, X.-H.**, J. Pan, M. He, T. Liu and J. Young, 2002, Role of Wind on the Estimation of Heat Flux Using Satellite Data. *J. Geophys. Res.* Submitted
12. Pan, J. **X.-H. Yan**, T. Liu, and M-X. He 2002, Calculation of the Sensible Heat Flux over the Global Ocean Using Satellite Data. *J. Geophys. Res.* Submitted

13. Jo, Y, and **X-H. Yan** 2002, Baroclinic Long - Waves in the North Pacific from the Heat Storage Anomaly Determined Using Altimeter Data. *Geophysical Research Letters*. In Review
14. Jo, Y. **X-H. Yan** 2002, Analysis of the evolution of meddies in the North Atlantic using floats experiments and multi-sensor data. *Deep Sea Research*, Submitted.
15. Zheng, Q. Shen, S. Y. Yuan, N. Huang, V. Klemas, **X-H Yan**, F. Shi, X. Zhang, Z. Zhao, 2003, Hai Nan, Evidence of upstream and downstream solitary wavetrains coexistence in the real atmosphere, *Geophys. Res. Lett.*, Submitted
16. Jo, Y and **X-H. Yan**, 2003. A Study of the Heat Storage Anomaly in the Tropical Atlantic Using Altimeter Data. *J. Geophys. Res.* Submitted.
17. Jo, Y., **X-H. Yan**, J. Pan, W.T. Liu and M-X. He, 2003, Sensible and Latent Heat Flux in the Tropical Pacific from Satellite Multi-Sensor Data. *Remote Sensing of Environment*, Submitted.
18. Pan, J. **X-H. Yan**, Jo, Y., Q. Zheng, and W.T. Liu, 2003, A New Method for Estimation of the Sensible Heat Flux under Unstable Conditions using Satellite Vector Winds, *J. Phys. Oceanogr.*, Submitted
19. Zhou, Y. **X-H. Yan**, X. Ding, X. Liao, D. Zheng, J. Pan, M. Fang, M. He and W.T. Liu, 2003 Can the migration of Pacific warm pool affect the Earth's wobble? *Earth and Planetary Science*, Submitted
20. **Yan, X.-H.**, and Jo, Y. 2003, A New Study of the Mediterranean Outflow and Meddies at 400-meter Isopycnal Surface using Multi-Sensor Data. *J. Geophys. Res.*, Submitted

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